即兴演奏的心理模型及其神经机制

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摘　要 即兴演奏是一个复杂的认知过程，其目标是为了创造出流畅并具有美感的音乐序列。即兴演奏需要使用大量的大脑网络来设计、产生和监控新的音乐输出，受到艺术表演者水平、创作条件要求等因素的影响，即兴演奏会出现两种不同的模式——认知控制模式和自动化加工模式。聚焦于两种不同的即兴演奏模式和其主要激活大脑区域，综述了即兴演奏的神经机制的研究，并提出了即兴演奏的双模式的心理模型。未来的研究可以重点关注即兴演奏的研究方法、即兴演奏两种模式的转换、即兴演奏和机器学习，以及即兴演奏对教育的启发意义等方面。

关键词 即兴演奏，认知控制，创造力，神经机制

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1　引言

即兴演奏(improvisation)是19世纪兴起的一种抒情特性音乐，指没有经过深思熟虑的构思，而是根据即时的思维想象和素有的文化沉积，临时发生兴致进行的音乐创作和演绎(夏征农, 2011; 王天, 2020)。即兴演奏是以目标为导向，以创造力为基础，结合感知觉编码、记忆提取、感觉监控、运动规划和社会互动的复杂的认知过程(Chen et al., 2020; Faber & McIntosh, 2020)，其目标是为了创造出流畅并具有美感的音乐序列。艺术表演者如何即兴演奏不仅与音乐心理学有关，而且和创造心理学也有紧密的联系(Beaty, 2015; Beaty et al., 2016)。在即兴演奏过程中，个体使用大量的大脑网络来设计、产生和监控新的音乐输出，这为研究者提供了一个窗口来观察创造性任务过程中的大脑活动。研究发现即兴演奏并不是一成不变的，其可能会出现两种模式，在专业技能水平较高，更加自由的环境下，即兴演奏可能会进入更加自我的状态，即较少的认知控制(Rosen et al., 2020; Limb & Braun, 2008; Pinho et al., 2014; Tachibana et al., 2019); 而在专业技能水平较低，较大的约束条件下，艺术表演者可能需要按照任务要求进行即兴演奏，会出现较强的认知控制(Bengtsson et al., 2007; de Manzano & Ullén, 2012a; Donnay et al., 2014)。

即兴演奏的研究发现了大量的相关脑区被激活，但是有两个脑区一直是研究者所争论的焦点，一是背外侧前额叶(dorsolateral prefrontal cortex, dlPFC)——在即兴演奏过程的认知控

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制加工中被显著激活; 二是内侧前额叶(medial prefrontal cortex, mPFC)——在即兴演奏过程的自动化加工中被显著激活(Vergara et al., 2021; Rosen et al., 2020)。但是，二者究竟在即兴演奏中发挥怎样的作用？高度自由的即兴演奏和受限制的即兴演奏会使艺术表演者的大脑产生哪些不同的反应？新手表演者和专家表演者在即兴演奏过程中的大脑反应有何不同？个体和团体之间的即兴演奏是否存在区别？即兴演奏的复杂性如何评估？这些都是本研究所探讨的问题。

因此本研究将重点介绍近年来即兴演奏的认知神经科学研究进展，首先介绍即兴演奏的代表性理论模型; 其次从即兴演奏的认知过程阐述认知控制和自动化的即兴演奏模式所激活的大脑区域; 再次讨论即兴演奏的评价方法; 最后就即兴演奏研究所涉及的被试的熟练度、即兴演奏的自由度、即兴演奏的研究方法和即兴演奏对教育的启发意义等方面对未来的研究进行展望。

2 即兴演奏的理论模型

2.1 Pressing 的理论模型

Pressing 认为即兴演奏是一系列生成和评估的过程，包括一个专业领域的知识库(a domain-specific knowledge base)、参考过程(referent processes)、感知反馈(perceptual feedback)和错误纠正(error correction)(Beaty, 2015; Pressing, 1988; Pressing, 1998)。

知识库由存储在长时记忆中的分层的知识结构组成，为即兴演奏提供音乐元素。参考过程由即兴演奏过程的认知和情感组成。参考过程以知识库作为基础，负责音乐序列的编排和生成。感知反馈和错误纠正负责即兴演奏过程对输出音乐序列的调整。Pressing 认为即兴演奏就是将一系列的“事件簇”(event clusters)所组成的“流”(stream)编排成一个音乐序列的过程，受到参考过程、感知反馈和错误纠正的作用，当前和未来的即兴演奏被不断地调整以符合艺术表演者的心境和演奏环境(Pressing, 1988; Pressing, 1998)。

2.2 即兴演奏的三层理论模型

Marr(1983)的计算视觉理论认为一个复杂的信息处理任务可以被描述为三个层级，分别为最高的计算层级(解决这个信息处理任务的整体目标)、中间的算法层级(实现目标必须进行的认知过程)和最低的机制层级(实施认知过程所需的神经基础)。

Loui(2018)将计算视觉理论引入即兴演奏的研究中，Loui 认为即兴演奏同样可以被描述为三个层级，在计算层级，艺术表演者需要以自身的专业领域的知识库作为基础，将流畅并具有美感的音乐序列作为即兴演奏的整体目标；在算法层级，艺术表演者需要根据计算层级的目标，应用现有条件来完成音乐序列的输出，并不断地调整所输出的音乐序列；在实施层级，即兴演奏需要大脑的听觉感知-动作网络、默认模式网络和执行控制网络负责声音的解

析、音乐序列的编排和即兴演奏的监控。

2.3 即兴演奏的四层概念模型

即兴演奏的四层概念模型由 Faber 和 McIntosh (2020)提出，这个模型包括四个层次：两个自下而上的层次(输入网络和输出监控)和两个自上而下的层次(自发的创造力和社会即兴演奏)。尽管该模型以一种连续的、分层的结构呈现，但认知和神经网络可能在空间和时间上重叠(Faber & McIntosh, 2020)。

第一层是输入网络，负责听觉信号的输入和解析(Alluri et al., 2012; Toiviainen et al., 2014)。第二层是用于音乐输出监控和评估的网络，包括音乐的语法和语义处理(Fiveash & Luck, 2016; Canette et al., 2020)。第三层是一个管理音乐输出的网络，将音乐元素组合成一个新的并具有美感的音乐序列(Pinho et al., 2014; Limb & Braun, 2008)。第四层是社会即兴演奏，艺术表演者将社会认知和社会互动用于指导音乐序列的生成过程(Müller et al., 2013; Müller & Lindenberger, 2019; Donnay et al., 2014)。

2.4 现有理论总结

本研究基于上述理论和前人的研究(Beaty, 2015; Pressing, 1988; Pressing, 1998; Loui, 2018; Landau & Limb, 2017; Faber & McIntosh, 2020; Bengtsson et al., 2007; de Manzano & Ullén, 2012a; Tachibana et al., 2019; Liu et al., 2012; Dietrich, 2004)，总结提出了即兴演奏的心理模型(见图 1)。我们认为即兴演奏可以分为三个阶段：包括输入和提取阶段、处理阶段以及输出阶段。在输入和提取阶段以及输出阶段，所有即兴演奏的神经过程可能是类似的。但是，由于受到演奏自由度的限制和熟练程度等因素的影响，艺术表演者在处理阶段产生了不同的认知和神经活动。简言之，一部分艺术表演者出现了认知控制的增强，即对即兴演奏进行计划制定，并对其进行评估、监督和反馈(de Manzano & Ullén, 2012a; Donnay et al., 2014; Costagli et al., 2014)；而另一部分艺术表演者出现了认知控制的减弱，即在即兴演奏活动中出现了自动化的加工，进入了“心流状态”(mind-flow)——一种将个人精神力完全投注在某种活动上，并且忘记自我存在的意识状态，被研究者称之为“最佳体验”(Dietrich, 2004; Landau & Limb, 2017; Tachibana et al., 2019; Liu et al., 2012; Csikszentmihalyi, 1990)。但可能并非所有艺术表演者一直采用固定的即兴演奏模式，在影响因素的变化下，即兴演奏的心理过程也可能发生转变(如长期的训练可能让新手表演者过渡到自动化加工的即兴演奏状态，而较为限制性的演奏条件也可能会使专家表演者的认知控制加强)。

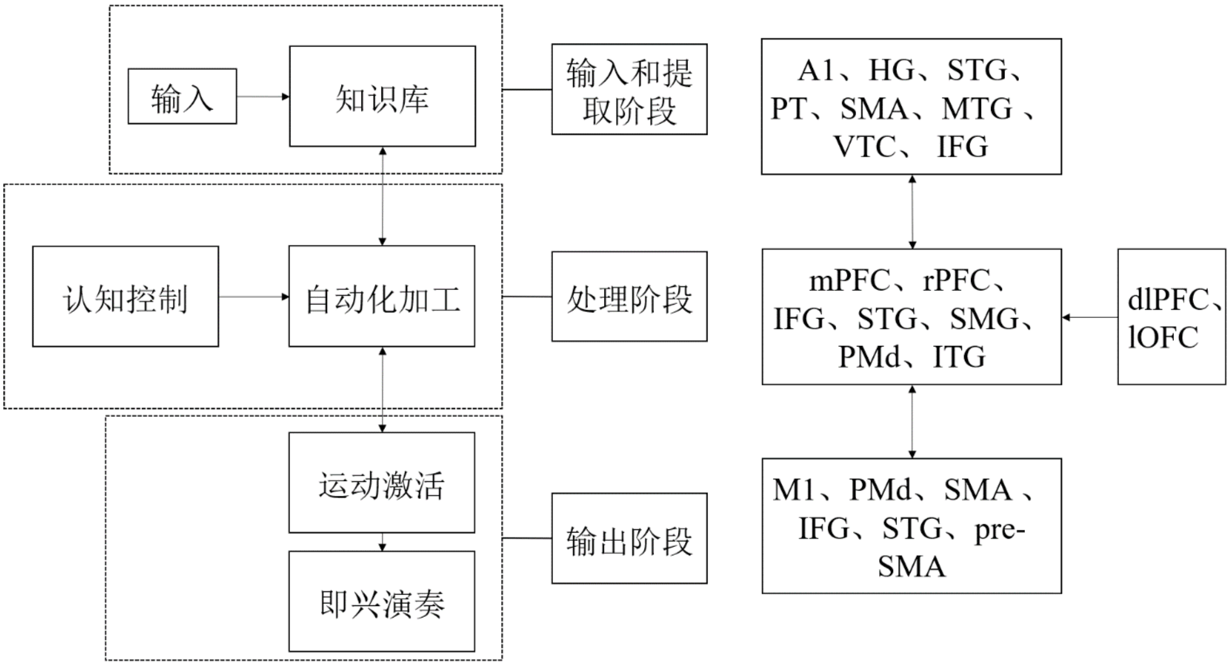

图 1 即兴演奏的心理模型及其神经基础

3 即兴演奏的神经机制

3.1 输入和提取阶段的神经活动基础

即兴演奏分为两种类型：有伴奏的即兴演奏和无伴奏的即兴演奏(Liu et al.， 2012; Berkowitz & Ansari, 2010)。在有伴奏的即兴演奏中，艺术表演者会先听到一个音乐序列，并以此为基础进行即兴演奏。当声音出现时，一个听觉有关的神经网络就会被激活，声音信号经由内侧膝状体(medial geniculate body, MGB)投射到初级听觉皮层(primary auditory cortex, A1)及更高级的脑区进行解析(姚小红, 熊鹰, 2004; Stanton & Harrison, 2000)，这一阶段为即兴演奏的输入阶段，主要激活的大脑区域为赫氏回(Heschl's gyrus, HG)、颞上回(superior temporal gyrus, STG)、颞中回(middle temporal gyrus, MTG)、前扣带回(anterior cingulate cortex, ACC)、缘上回(supramarginal gyrus, SMG)、腹侧颞叶皮层(ventral temporal cortex, VTC)、颞平面(planum temporale, PT)、基底神经节(basal ganglia)、小脑(cerebellum)、前岛叶(anterior insulae, AI)、背侧前运动皮层(dorsal premotor cortex, PMd)、前辅助运动区(pre-supplementary motor area, pre-SMA)、辅助运动区(supplementary motor area, SMA)、边缘系统(Limbic system)和胼胝体(corpus callosum) (Warren, 2008; Zatorre et al., 2007; Fadiga et al., 2009; Bodin et al., 2018; Koelsch et al., 2006; Siman-Tov et al., 2019; Bravo et al., 2020; Shi & Zhang, 2020; Benner et al., 2017; Ding et al., 2019; Schaal et al., 2015; Gaab et al., 2006; Zhang et al., 2017; Angulo-Perkins & Concha, 2014)。STG、HG、MTG 和 PT 与音高、音色和旋律信息的处理有关；STG、MTG、pre-SMA、SMA、基底神经节和小脑可能与节奏信

息的处理有关；STG、VTC、右侧 HG 和右侧 PT 可能和音色的处理有关；边缘系统和 AI 可能和声音情感信息的处理有关。这个神经网络在输入阶段接收、提取和解析听觉信号中的有用信息，为新的音乐序列的产生做准备。

在无伴奏的即兴演奏中，艺术表演者根据当时的演奏环境和自己的认知情感状态，自然而然地进行即兴演奏。艺术表演者的任务就是将自己的专业领域知识与主观(如表演者自身的情绪状态)和客观(如听众的反应)因素相结合，提取出与之相符的音乐元素。在这一阶段，主要激活的脑区为 PMd、ACC、STG、MTG、VTC、HG、额下回(Inferior Frontal Gyrus, IFG)小脑和胼胝体，负责专业领域知识中的声音信息的检索以及音乐序列生成之间的交互作用(Sammler et al., 2015; Becker et al., 2020; Berkowitz & Ansari, 2008; Berkowitz & Ansari, 2010; Wang et al., 2018; Teige et al., 2018; Whiteside et al., 2016; Kavé & Sapir-Yogev, 2020; Rauschecker, 2005)。因此无伴奏的即兴演奏会先跳过输入阶段的大脑活动，但并不意味着输入阶段的神经网络在无伴奏的即兴演奏中会停用。在即兴演奏开始之后，艺术表演者会听到自己演奏的音乐序列，此时，输入阶段的神经网络才会被激活。

3.2 处理阶段的神经活动基础

处理阶段是对输入的声音进行整合加工，并提取已有知识库的内容之后，产生新的音乐序列的过程。在这一阶段，不同的研究发现了艺术表演者采用了不同的即兴演奏方式。由于 mPFC(包含 pre-SMA、SMA 及 ACC)负责音乐序列的选择和编排，其几乎在所有的即兴演奏中都会被激活(或者至少部分激活) (Gläscher et al., 2012; Bolkan et al., 2017; Landau & Limb, 2017)。因此即兴演奏的认知控制模式和自动化加工模式可能与 dlPFC 的活动有关(Chrysikou et al., 2014; de Manzano & Ullén, 2012a; Berkowitz & Ansari, 2008; Sasaki et al., 2019)， 当 dlPFC 在即兴演奏中被激活时，mPFC 在音乐序列的生成过程受到 dlPFC 的评估和监督，此时的即兴演奏模式为认知控制模式，而当 dlPFC 在即兴演奏中失活时，mPFC 在音乐序列生成过程中不受限制，此时的即兴演奏模式为自动化加工模式(McPherson et al., 2016; Pinho et al., 2014; Tachibana et al., 2019; Landau & Limb, 2017; Limb & Braun, 2008; Moghaddam & Homayoun, 2008)。

3.2.1 **认知控制主导的即兴演奏**

即兴演奏的自由度影响艺术表演者对即兴活动的认知控制，在实验条件要求较为严格时，dlPFC 被强烈激活。Bengtsson 等人(2007)采用了将即兴演奏与记忆提取进行对比的实验方法，与其他研究采用的自由演奏不同(Donnay et al., 2014; Limb & Braun, 2008; Liu et al., 2012)，他们仅允许艺术表演者根据视觉提示的八小节旋律进行即兴演奏，为了控制额外变量的干扰，艺术表演者的记忆提取内容为先前在扫描仪中即兴演奏的旋律。Bengtsson 等人报告了在即

兴演奏过程中主要激活的大脑区域，包括 dlPFC、pre-SMA、PMd 和 STG。作者认为，dlPFC 在选择性注意、感觉监控和运动序列的生成过程中与 pre-SMA、PMd 相互作用，并和 STG(听觉工作记忆相关)共同作用于听觉-运动的整合和音乐序列的生成(Bengtsson et al., 2007)。

专业技能影响即兴演奏的表现和神经活动，较低的专业技能水平预测了即兴演奏过程中的较强的认知控制。de Manzano 和 Ullén (2012a)发现了新手表演者的 dlPFC、外侧眶额皮层(lateral Orbitofrontal cortex, lOFC)、左侧 IFG、ACC、pre-SMA、SMA、脑岛和小脑等脑区的激活在即兴演奏中增加。IFG、ACC、SMA 和小脑的激活可能反映了专业领域知识的检索、音乐语法的选择和处理以及听觉-运动序列的选择和生成(Berkowitz & Ansari, 2010)。dlPFC 的活动可能反映了对当前和计划中的即兴演奏活动的执行控制和监督反馈(Jones & Graff-Radford, 2021)。为了进一步探究 dlPFC 的活动对新手和专家表演者的影响，Rosen 等人(2016)使用经颅磁直流电刺激(tDCS)来干预右侧 dlPFC 的活动，发现在阳性刺激下，专家表演者的即兴演奏水平有所下降，但新手表演者的即兴演奏水平有所提高。Rosen 认为专家表演者是由 mPFC 主导的自动化即兴演奏模式，dlPFC 的阳性刺激可能会造成控制性加工的唤醒，干扰其当前的演奏状态，造成演奏水平下降；而新手表演者的专业知识和认知能力不足以实现高水平的自动演奏，阳性刺激可能会提高即兴演奏时右侧 dlPFC 的活动效率，允许自上而下的认知控制和行动选择，从而提高即兴演奏水平(Ivancovsky et al., 2019; Pinho et al., 2016)。

在团体即兴演奏中，艺术表演者需要根据合作者所演奏的音乐序列不断调整自身的演奏。因此，艺术表演者不仅要将注意力分配给内部(如生成性)资源，还需要将大量注意力分配给外部(如交际性)资源(Beaty, 2015; Donnay et al., 2014; Walton et al., 2018)。Donnay 等人(2014)要求专家表演者进行“交换的四小节”(trading fours)表演——表演者轮流表演四小节音乐片段。发现在团体即兴演奏中左侧 IFG、STG、dlPFC、SMA、小脑等脑区的激活增加；而背侧额中回(medial frontal gyrus, MFG)、内侧 SFG(superior frontal gyrus, SFG)和双侧角回(angular gyrus, AG)的激活降低。IFG 和 dlPFC 的激活可能反映了对合作者的即兴演奏的监控(Whitehead et al., 2019)。STG 的激活可能和工作记忆中保存上一位艺术表演者的音乐序列有关(Beaman et al., 2007)，而 MFG 和 SFG 的失活可能反映了专家表演者自动化加工的即兴演奏状态(Donnay et al., 2014)。角回和自然语言的语义处理有关(Platel et al., 2003; Lewis et al., 2019)，角回的失活可能表明音乐语义和自然语言语义有本质不同。行为学数据分析发现艺术表演者在团体即兴演奏中使用的音符、节奏和旋律具有显著的相关性，说明艺术表演者之间产生了互动(Donnay et al., 2014; Walton et al., 2018)。

在新手表演者的即兴演奏过程中，出现了右侧额叶、右侧颞顶联合区和右侧顶枕区的beta(13~28Hz)频段和gamma(28~100 Hz)频段的神经振荡增强(Rosen et al., 2020)。Beta神经振荡被认为与注意力的集中、自上而下的控制及执行功能的产生和维持有关(Rosen et al., 2020; Engel & Fries, 2010; Rimmele et al., 2019; Richter et al., 2017; 叶超群 等, 2021)，反映了新手表演者在即兴演奏中的认知控制加工。有趣的是，虽然Berkowitz和Ansari(2010)发现专家表演者的右侧颞顶联合区在即兴演奏期间出现失活，但他们却做出了相反的解释Berkowitz和Ansari认为右侧颞顶联合区的活动反映了自下而上的刺激驱动的加工过程(Shulman et al., 2007; Corbetta et al., 2008)，专家表演者右侧颞顶联合区的失活则说明了其目标导向的即兴演奏过程。因此，关于右侧颞顶联合区在即兴演奏过程中的作用可能还需要进一步的探究。

3.2.2 自动化加工主导的即兴演奏

根据以上研究可以发现，涉及dlPFC激活的即兴演奏都需要较高程度的认知控制，如在较大的约束条件下进行即兴演奏，艺术表演者需要关注即兴演奏不会超出约束条件；或者是较低的即兴演奏水平造成了对即兴演奏的音乐序列的评估、监控和反馈；亦或者是在团体表演中，需要与合作者交流，并调整自身的即兴演奏。在去除这些因素之后，艺术表演者可能会进行不受条件限制的自动化的即兴演奏。因此，mPFC主导的自动化加工的即兴演奏可能需要两个条件：较高的专业技能以及较为自由的演奏环境。以此为基础，艺术表演者才能够进入完全忘我的即兴演奏状态，在这种状态下，音乐元素在工作记忆中被自动化处理为可以由运动皮层执行的运动序列，从而使艺术表演者能够流畅地、自然而然地完成音乐序列的输出。从dlPFC主导的认知控制加工到mPFC主导的自动化加工的转变，带来了一个艺术表演者即兴演奏的质的变化(Landau & Limb, 2017; Chein & Schneider, 2005)

研究者们发现，在高度自由的即兴演奏中，专家表演者的lOFC和dlPFC激活降低，左侧IFG、ACC、PMd、STG、MTG、喙外侧前额叶(rostrol prefrontal cortex, rPFC)、mPFC激活增加(Tachibana et al., 2019; McPherson et al., 2016; Limb & Braun, 2008; Bashwiner et al., 2020)，默认模式网络(default mode network, DMN)和pre-SMA、SMA、PMd及dlPFC之间的连接增强(Pinho et al., 2016)。lOFC和dlPFC激活降低可能反映了抑制或监测过程的暂停(Pinho et al., 2014)；IFG和STG的活动可能反映了对音乐的理解以及音乐句法的处理过程(Fadiga et al., 2009; Zhang et al., 2017)；mPFC的活动可能反映了对音乐的内化和自动化加工的认知过程(McPherson et al., 2016; Limb & Braun, 2008)；而rPFC的活动可能反映了自发性思维及自传表达过程(Landau & Limb, 2017; Dumontheil et al., 2010; Kreplin & Fairclough, 2015)；DMN和其他脑区之间的连接增强可能反映了对音乐结构更有效的整合(Pinho et al.,

2014; Pinho et al., 2016)。

对专家表演者的旋律或节奏即兴演奏的研究发现，二者激活了相似的大脑区域，包括 ACC、IFG 和前运动皮层(pre-motor cortex, PMC)等(Berkowitz & Ansari, 2008)。Berkowitz 和 Ansari 认为 IFG 和腹侧 PMC 负责音乐语言的分析和声音序列的选择(Brown et al., 2006)，IFG 和 ACC 负责声音序列的生成，背侧 PMC 负责运动规划和执行过程。但令人意外的是，在输入阶段，旋律和节奏信息的解析却由不同的大脑区域负责(Warren, 2008)。一个可能解释是，运动皮层既参与了节奏信息的解析，又参与了节奏和旋律的即兴演奏过程(Zatorre et al., 2007)。Liu 等人(2012)还探究了人声即兴演奏的神经过程，他们以专业的说唱歌手作为被试，比较了其在记忆提取(rehearsed)和即兴演奏(freestyle)过程中的功能磁共振成像(functional magnetic resonance imaging, fMRI)。作者发现在即兴演奏过程中 PMd、STG、SMG、左 IFG、pre-SMA、ACC、杏仁核(amygdala)和 mPFC 等脑区的激活增加，dlPFC 的激活降低。脑功能连接特性分析显示扣带回运动区(cingulated motor areas, CMA)、外侧裂周区皮层(perisylvian cortices)、杏仁核和 mPFC 在即兴演奏中连接性增强。这种大脑活动被认为反映了一个连接动机、语言、情感和动作的网络(Liu et al., 2012)。

EEG(Electroencephalogram)研究发现，专家表演者自动化加工主导的即兴演奏与右侧额叶的 theta(4~8 Hz)和 alpha (8~12 Hz)频段神经振荡相关(Rosen et al., 2020; Boasen et al., 2018)。额叶 alpha 神经振荡的活动与血氧水平依赖(blood oxygen level dependent, BOLD)信号的减少有关，其可能反映了皮层活动的减少(Pitchford & Arnell, 2019; Lopata et al., 2017)。Alpha 神经振荡被认为代表了一种自上而下的抑制过程，降低了当前任务不需要的大脑区域的活动，有研究者将其描述为“皮质空转”(Brown & Marsden, 1999; Cheng et al., 2020; Lopata et al., 2017)。创造力的低唤醒理论(low arousal theory of creativity)认为当个体处在低皮质唤醒及较低水平的认知控制状态时，更容易产生有创造力的想法(Martindale, 1999)。因此，认知控制的减少可能允许艺术表演者快速选择音乐材料以产生新的音乐序列(Forstmann et al., 2006)。而最近的研究发现，额叶 alpha 神经振荡的增加可能反应了发散思维、抑制控制、注意力的内部集中等积极的大脑认知加工过程(叶超群 等, 2021; Fink & Benedek, 2014; Lopata et al., 2017; Benedek et al., 2011; Bengson et al., 2020; Lustenberger et al., 2015; Benedek et al., 2014)。这样一种创造性的精神状态可能与更高质量的即兴演奏相关(Adhikari et al., 2016; Lopata et al., 2017)。

3.2.3 即兴演奏——认知控制还是自动化加工？

由于 mPFC 和自我有关，允许个体在没有主动思考时进行自我参照加工(杨帅 等, 2012; Wang et al., 2020; Andrews-Hanna et al., 2014; Gerlach et al., 2014; Spreng & Grady, 2010)。艺术

表演者在根据自身的情感状态和专业领域知识进行即兴演奏时，mPFC 可能会在这种自我表达的即兴演奏状态中起主导作用。而当艺术表演者需要根据表演环境对即兴演奏进行调整，或者专业领域知识不足需要认知控制网络(cognitive control network, CCN)的辅助加工时，dlPFC 便会被激活。因此想要达到真正的即兴演奏状态可能并非需要刻意地将 dlPFC 从即兴演奏中分离，而是要求增长专业领域的知识和增加即兴演奏的自由度，使得 mPFC 在即兴演奏中发挥主导作用，从而“绕过”dlPFC 的认知控制加工(Liu et al., 2012)，艺术表演者才能在即兴演奏时进入“心流状态”并与音乐建立更直接的联系(Csikszentmihalyi et al., 2013)。

虽然即兴演奏期间的自动化加工和执行控制加工可能表现为一种相互对抗的状态，但大量与即兴演奏类似的研究(如即兴绘画、即兴喜剧和即兴舞蹈等)发现，dlPFC 主导的控制性加工网络和 mPFC 主导的自动化加工网络出现了交互(Chen et al., 2020; Saggar et al., 2015; Fink et al., 2009; Zhang et al., 2020; Beaty et al., 2014; Ellamil et al., 2012; Morse et al., 2018; Brawer & Amir, 2021; Cohen & Maunsell, 2011; Lewis & Lovatt, 2013)。说明不同的认知过程并不是由单一的皮层区域负责的，或者说不同的皮层区域并不只负责的特定的认知过程。相反，大部分的大脑区域都在所参与的认知任务中相互作用(Cocchi et al., 2013; Bassett & Sporns, 2017; Gu et al., 2021; de Manzano & Ullén, 2012a; Pinho et al., 2014)。因此，dlPFC 和 mPFC 的活动模式可能体现了对当前任务的不同参与程度，使艺术表演者能够流畅地完成即兴演奏各阶段的心理过程，从而产生流畅的并具有美感的音乐序列(Vergara et al., 2021; Lopata et al., 2017; Tsunada et al., 2019)。

3.3 输出阶段神经活动基础

输出阶段是在对即兴演奏的旋律和节奏等信息进行加工整合之后，对音乐序列进行运动生成和输出表达的过程。在该阶段做出主要贡献的是基底神经节、小脑、pre-SMA、SMA、PMd 和初级运动皮层(primary motor cortex, M1)，这几个区域是即兴演奏和非即兴的演奏活动中所共同激活的脑区，参与组织、协调和执行新的运动序列(Bari et al., 2013; Bischoff-Grethe et al., 2004; Bengtsson et al., 2007; Liu et al., 2012; Botvinick, 2004)。PMd 和 pre-SMA 负责运动准备、规划和控制(de Manzano & Ullén, 2012b; Kennerley et al., 2004)；SMA 和 M1 负责连续动作的执行(Watson, 2006)；基底神经节和小脑负责将单个动作整合成统一的运动序列(Zatorre et al., 2007; Pope et al., 2005; Penhune & Doyon, 2005)。由于 pre-SMA 和 PMd 分别负责运动序列的时间(Karabanov et al., 2009)和空间信息(Bapi et al., 2006)的感知和学习，在此基础上，de Manzano 和 Ullén (2012b)通过限制即兴演奏的旋律性或节奏性探索了 pre-SMA 和 PMd 在运动序列生成过程中的不同指向性，发现 pre-SMA 参与了旋律性和节奏性即兴演奏，而 PMd 只参与旋律性即兴演奏。

伪随机演奏和即兴演奏的区别在于创造性音乐序列的生成，所以二者共同激活的脑区可能代表了音乐序列的生成和输出表达的认知过程，其中包括 ACC、pre-SMA、STG、IFG、双侧脑岛、左下顶叶(inferior parietal lobe, IPL)、前运动皮层(pre-motor cortex, PMC)和小脑(de Manzano & Ullén, 2012a)。这些大脑区域可能负责运动序列的生成和执行、动作的感知和监测、行为的调整以及对重复反应的抑制(de Manzano & Ullén, 2012a; Pinho et al., 2014; Nathaniel-James et al., 2002; Bartolo & Averbeck, 2020; Bari & Robbins, 2013)。但是，即兴演奏所体现的创造性认知过程可能不限于和伪随机演奏这类非创造性认知过程存在空间上的重叠，二者最根本的区别可能反映在大脑活动的时间和空间特征上，或者说即兴演奏可能依赖于大脑功能模式的改变，但这种功能模式的特征和影响因素还需要进一步的探究。

4 即兴演奏的评估

在较早的即兴演奏研究中，评价即兴演奏创造性一般由多个评分者进行主观评估，但近年已经有研究者将熵(entropy)作为一种信息论的评估方法引入了即兴演奏的研究中(Daikoku, 2018; Loui, 2018; Nakayama et al., 2020)。熵是热力学中表征物质状态的参量之一，其物理意义是体系混乱程度的度量(黄泽徽 等, 2011)，因此熵被定义为每次即兴演奏中音符的变化性(Loui, 2018; Zeng et al., 2017)，熵的公式为:$H(X)=-\Sigma pi*\log(pi)$，pi 指每个音符的概率(Loui, 2018; Dolan et al., 2018; Nakayama et al., 2020)。在即兴演奏过程中如果只演奏一个音符(pi=1)，熵 H(X)=0，而演奏变化的音符则会产生一个正熵值(Loui, 2018)。但是根据熵增定律，熵的最大状态，也就是系统的最混乱无序状态(董春雨, 姜璐, 1997)，因此另外一个参量——流畅性(fluency)也被引入即兴演奏的评价中，流畅性

每次即兴演奏中音符的数量。研究发现，流畅性和熵与艺术表演者即兴演奏的创造力具有显著正相关(Zeng et al., 2017; Koelsch et al., 2000; Loui, 2018)。

在神经层面上，研究者们探究了流畅性、熵和灰质及白质体积的关系(Zeng et al., 2017; Arkin et al., 2019; Daikoku, 2018; Loui, 2018; Chen et al., 2014; Shi et al ., 2017; Sunavsky & Poppenk, 2020)，但是不同的研究却得出了相反的结论。我们认为可能是由于熵和流畅性将即兴演奏这一复杂的认知过程的评价标准过于简化，才导致研究者们所发现的结果相互矛盾。因此，虽然熵和流畅性为我们提供了一个客观的、量化的即兴演奏创造力的评估方法，但其缺乏对音乐特质和音乐序列的整体考虑(喻意, 2017)。最大熵只需要在乐器上完全随机演奏，而最大流畅性只需要在即兴演奏中尽可能多地演奏音符(Loui, 2018)，单独来看，最大熵或者最大流畅性带来的都是十分混乱的声音序列。但不可否认的是，熵和流畅性是即兴演奏所引入的第一个客观评价方法，未来的工作仍需要进一步探究如何通过客观手段对即兴演奏的创造力和复杂性进行量化和质化的评价。

5 总结与展望

国外的研究者们对即兴演奏的探索已经取得了很多重要的进展，包括即兴演奏的特点、类型、评估方法以及认知与神经机制等，但国内的研究还比较少。即兴演奏的研究不仅有利于扩展我们对音乐和创造性认知过程的了解，也有助于将即兴演奏工具化为教育的手段。未来的研究可从以下几方面进一步展开。

5.1 即兴演奏的研究方法

即兴演奏的研究尚未出现成熟的研究范式，大多数研究者采用的方法是即兴演奏和音乐序列回忆的对比。但这种研究方法可能会带来以下几个问题：(1)艺术表演者擅长的乐器不同带来的认知和神经活动的差异；(2)即兴演奏和旋律回忆在认知和神经活动中可能会出现重叠，也就是说即兴演奏减去旋律回忆并不能代表真正的“即兴过程”；(3)即兴演奏太过于“自由”的表达，造成艺术表演者会重复熟悉的音乐序列(Müller & Lindenberger, 2019; Liu et al., 2012)，但是过多的控制(如节拍和音符的限制)又会限制艺术表演者的即兴演奏(Bengtsson et al., 2007)。因此，有研究者认为可以从实验任务中移除即兴演奏(McPherson, et al., 2013; Dhakal et al., 2019; Sasaki et al., 2019; Loui et al., 2015)，通过向不同水平的艺术表演者(组间变量)呈现不同常规性(组内变量)的音乐材料(Koelsch, 2009; Przysinda et al., 2017)，观察艺术表演者的组间和组内反应是否有显著差异。并且，可以向艺术表演者呈现被删除部分片段的音乐序列，并要求艺术表演者将该音乐序列补充完整，评价补充后音乐序列的创造性。

5.2 即兴演奏两种模式的转换

即兴演奏需要同时执行几个过程，包括感觉和知觉编码、记忆提取、感觉监控、运动规划等(Beaty, 2015)，长期的练习会使这些过程的认知控制加工部分转化为自动化加工，让新手表演者逐渐成为专家表演者(Kleinmintz et al., 2014; Loui, 2018; Faber & McIntosh, 2020; Sowden et al., 2015)。但是，一方面，需要多长时间的即兴演奏练习才能够完成新手表演者到专家表演者的转换我们尚不清楚；另一方面，在实验控制条件下，多高程度的即兴演奏任务的条件要求会导致专家表演者从自动化加工转换为控制性加工，并且转换时神经活动发生的变化也是让人十分好奇的。因此, 未来研究不妨以多组不同即兴演奏时长的艺术表演者作为研究对象，探索即兴演奏时间对大脑功能结构和即兴演奏能力的塑造作用(Arkin et al., 2019; Habibi et al., 2018; Herholz & Zatorre, 2012)。在实验范式上，可以设计具有更高变化性的研究范式，同时可以结合较高时间和空间分辨率的脑磁图(magnetoencephalogram, MEG)技术，探索艺术表演者在随实验条件变化下即兴演奏模式的变化以及相关的神经活动。

5.3 即兴演奏和机器学习

由于即兴演奏的表演和训练效果的评价尚未形成统一的客观测量方法，而基于即兴演奏

的音乐序列和脑成像的机器学习或许能够为其提供新的方向。机器学习可以提取即兴演奏的音乐序列及相关的脑成像数据的一般特征，例如 Sasaki 等人(2019)使用共同空间模式算法(common spatial patterns, CSP)进行脑电图特征提取的机器学习，对艺术表演者的即兴演奏与音阶交替的分类正确率超过 75%。Sasaki 等人认为可以使用神经反馈和神经调节方法开发基于神经工程学的技术，从而改善即兴演奏的训练和表现，并且可以将艺术表演者的大脑相关活动用于判断即兴演奏状态，为即兴演奏提供更加客观的评价方法。未来的研究可以将机器学习应用于即兴演奏的脑结构成像数据(如大脑灰质体积、白质体积、皮层厚度及弥散张量成像)及艺术表演者的面部表情和肢体动作数据等，并且研究者可以在获得大样本数据的基础上, 尝试使用深度学习的方法进行分类, 探究即兴演奏的内在机制(Sasaki et al., 2019; 郑泓等, 2020)。

5.4 即兴演奏对教育的启发意义

鉴于即兴演奏训练对认知能力和大脑功能结构的影响(Pinho et al., 2014; Tachibana et al., 2019; Rosen et al., 2016)，其能否像工作记忆训练一样对其他能力产生迁移效应(Klingberg, 2010; Teixeira-Santos et al., 2019; Au et al., 2015)是一个很有前景的研究方向。

一方面，Lopata 等人(2017)发现，长时间的即兴演奏训练不仅可以改善艺术表演者的即兴演奏水平，而且可以提高与音乐能力无关的创造力测验水平。而其他需要即兴能力的艺术创作，如喜剧表演(Brawer & Amir, 2021)、美术(Ellamil et al., 2012)、舞蹈(Christensen et al., 2021)、文学(Chen et al., 2020)甚至医护人员的执行操作(Martínez-Gómiz et al., 2021; Coste et al., 2019)等是否也能够通过相关的即兴创作训练得到提高。并且，由于创造力可以预测个体的工作记忆(Liu & Shi, 2007)和学业表现(Marjoribanks, 1976)，从长远来看，挖掘如何进行即兴演奏训练才能够有效地提高创造力水平具有很强的教育意义。

另一方面，由于孤独症谱系障碍(autism spectrum disorders, ASD)、注意缺陷与多动障碍(attention deficit and hyperactivity disorder, ADHD)及发展性阅读障碍(developmental dyslexia, DD)等发育障碍临床表现多变(Deciphering Developmental Disorders Study, 2015)，并且也尚未形成统一的干预方法，医生和科研人员针对这类发育障碍尝试了多种治疗方法, 积累了很多经验。常见的治疗方法有行为干预法、特殊教育法、药物治疗法、生物医学干预法以及心理干预法等(段云峰, 等 2015; Lai et al., 2014; Biederman & Faraone, 2005; Peterson & Pennington, 2012)。而即兴演奏可能为当前发育障碍儿童的干预训练提供新的思路(Trepanier & Nordgren, 2017; Ciambella et al., 2019; Bieleninik et al., 2017; Crawford et al., 2017)。如即兴演奏训练可以改善 ASD 儿童和智力障碍儿童的社会功能(Mayer-Benarous et al., 2021; Sharda et al., 2018)以及 ADHD 儿童运动冲动和在课堂上的多动表现(Rickson, 2006)。但是较小的样本量和相互矛

盾的结果(Mayer-Benarous et al., 2021; Bieleninik et al., 2017)也削弱了这些研究的说服力，我们认为应该进行更多关于发育障碍儿童的即兴演奏干预研究来证实其效果。

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The psychological model and neural mechanism of improvisation

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Abstract: Improvisation is a complex cognitive process that employs numerous of brain networks to devise, generate and monitor esthetically appealing and novel musical output. Influenced by the skill of the improvising musician, the performance requirements and other factors, improvising musician may have two cognitive modes, namely, cognitive control mode or automatic processing mode. Focusing on the two different improvisation modes and the main employed brain regions, research on the neural mechanism of improvisation were reviewed. Furthermore, a dual-mode of improvisation was proposed. Future research may focus on aspects of the research methods of improvisation, the conversion of the two modes of improvisation, improvisation and machine learning, and the significance of improvisation in education, among others.

Key words: improvisation, cognitive control, creativity, neural mechanism